UNITED STATES PATENT APPLICATION

For

NOISE REDUCTION FOR SPECTROSCOPIC SIGNAL PROCESSING

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NOISE REDUCTION FOR SPECTROSCOPIC SIGNAL PROCESSING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. provisional application, Serial No. 60/443,086, filed on January 28, 2003, entitled "Producing Windowed Noise Reduced Signals for Fourier and High Resolution Signal Processing for Spectroscopies such as NMR, ICR, etc.," and U.S. provisional application, Serial No. 60/445,671, filed on February 7, 2003, entitled "Producing Windowed Noise Reduced Signals for Fourier and High Resolution Signal Processing for Spectroscopies such as NMR, ICR, etc." The entire content of both applications is incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] *Field of Invention*

[0003] The present invention relates to signal processing in NMR and other spectroscopic techniques.

[0004] *Background*

[0005] In NMR spectroscopy, as well as in other spectroscopic methods, noise reduction can be a serious problem. In most experimental NMR studies, excessive noise can be present in the measured time domain signal, which decays exponentially and is thus called an FID ("free induction decay") signal. Because of the noise, the Fourier transformed spectrum may not allow the underlying spectrum to be reliably differentiated or extracted from the noise.

[0006] A number of methods are known in the art for reducing noise in NMR studies. Signal averaging over many transients or scans is widely known. In signal averaging, however, the signal grows relatively slowly over time. Also, other factors such as sample concentration, magnetic field strength, and NMR machine design frequently affect the intensity of the NMR signal, which is inherently rather weak. Because of these factors, the needed number of transients may often be very high. When the fast Fourier transform method is used to derive the spectrum from the measured data, the

requisite number of transients may be too high for certain experiments to be practically feasible.

[0007] Many attempts have been made to address this problem by developing data processing methods that can extract signal information from noisy data using available knowledge regarding the model for the underlying signal. One known method is harmonic inversion, which is a parameter fitting model that extracts the desired spectral parameters by fitting the data to a sum of damped harmonics. The knowledge used here is that a linear combination of complex decaying exponentials can be assumed to be a good model for an NMR FID signal. The equations that relate the measured FID signal to such a model directly yield, when solved, spectral parameters such as the position, width, and intensity of each nuclear resonance, so that a spectrum can be reconstructed from these parameters.

[0008] The harmonic inversion method achieves a higher spectral resolution, for a given signal length, compared to the Fourier transform method. The solutions to the harmonic inversion equations, however, can be extremely sensitive to small noise perturbations. Various regularization techniques have been proposed. With no noise or with very little noise, the harmonic inversion method usually provides acceptable results when used with these regularization schemes. At typical noise levels, however, the harmonic inversion method together with the regularization schemes may yield inconsistent and unreliable results, producing spectra with false or missing spectral lines.

[0009] For these reasons, there is a need for a method and system that allows reliable spectra to be derived from spectroscopic data, without requiring an excessive number of transient acquisitions.

SUMMARY

[0010] A method and system is presented that is based on harmonic inversion, and that allows for a reliable spectrum to be obtained using a greatly reduced number of transients or signal measurements. By providing criteria for recognizing when to stop transient collection, the machine time that is required in order to measure a spectrum to

a requisite degree of accuracy, and to implement harmonic inversion reliably, can be significantly reduced.

[0011] In one embodiment, the NMR response signal from a sample is measured, and the measured signal is averaged over a number of measurements. The averaged signal is written as a sum of a noisefree component and a noise component, and is used to create a vector space that has a noisefree subspace and a noise subspace. A correlation matrix is created within the vector space. The correlation matrix is diagonalized, to yield the singular values and their corresponding eigenvectors. The singular values, which include noisefree singular values associated with the noisefree subspace, and noise singular values associated with the noise subspace, are plotted in a graph.

[0012] The appearance and subsequent stabilization of a clear gap between a noisefree singular value and a noise singular value are criteria that establish that a sufficient number of transients have been acquired. When the gap stabilizes, the measured signal is projected onto the noisefree subspace to produce a noise-reduced signal, which is then frequency converted by harmonic inversion or by other signal processing methods (such as Fourier transform), to generate a noise-reduced spectrum.

[0013] Instead of monitoring the signal-to-ratio of the spectrum as more measurements are made and averaged over, as done in other methods known in the art, in the present method and system, the criterion for stopping the acquisition of transients is the appearance of a stable gap in the singular value graph, and the appearance of a stable spectrum thereafter.

[0014] The method and system described above reduces the number of transients required to obtain satisfactory NMR spectra by a factor of about 10 to about 100, compared to a method in which signal averaging is performed using Fourier transforms only.

BRIEF DESCRIPTION OF THE DRAWINGS

[0015] FIG. 1 is a schematic block diagram of an apparatus for performing spectral analysis, in accordance with one embodiment.

[0016] Fig. 2 illustrates the 1D ^{13}C NMR absorption spectrum of a 15 mM solution of strychnine in $CDC_{l3,}$ for a carbonyl spectral region, and with signal after 128 transients (first column) and 256 transients (second column), of length N = 16384.

[0017] Fig. 3 illustrates the logarithmic singular value curves, calculated to obtain the 1D ^{13}C NMR absorption spectrum of a 15 mM solution of strychnine in CDC_{l3} for a carbonyl spectral region, as shown in Fig. 2.

[0018] Fig. 4 illustrates a 1D INADEQUATE, spin-spin interaction ^{13}C-^{13}C spectrum of a 5% solution of dicyclopentadiene in $CDC1_{3,}$ for the 4th carbon spectral region for a noisy signal after 2432 and 2560 scans of length $N = 32K$.

[0019] Fig. 5 illustrates the logarithmic singular value curves calculated for the experimental data presented in the left (2432 scans) and right (2560 scans) columns of Fig. 4.

DETAILED DESCRIPTION

[0020] A method and system is presented that links the termination of transient acquisitions to the appearance of a gap in a singular value plot made from previously measured data, rather than to the signal-to-noise ratio of the resulting spectrum.

[0021] FIG. 1 is a schematic block diagram of an apparatus 100 for performing spectral analysis of a sample, in accordance with one embodiment. The apparatus 100 generates the characteristic spectra of one or more constituents of the sample, by applying an excitation energy to the sample, measuring the signals emitted by the sample in response to the applied excitation energy, and processing the signals to generate the desired spectrum. Usually, the excitation energy takes the form of a sequence of RF excitation pulses, although in some spectroscopic techniques such as continuous wave NMR spectroscopy, a continuous wave of excitation energy may be applied. In one embodiment, the apparatus 100 is an NMR apparatus for performing NMR spectroscopy. While an NMR apparatus will be described in this section, it should

be noted that the system and method of the present invention is not limited to NMR spectroscopy, and can also be used in conjunction with spectroscopic techniques, other than NMR, which use signal averaging to reduce noise.

[0022] In overview, the NMR apparatus 100 includes a data acquisition system 105 that measures the response signals emitted by the sample in response to the RF excitation pulses that have been applied thereto, and a data processing system 107 that processes the measured signals to generate the desired characteristic spectra for the constituents of the sample. The signal averaging method, well known in the art, is used. The signals are averaged over a large number of measurements or scans (called "transients" in NMR spectroscopy) in order to lower the noise content compared to a single signal measurement or transient. The apparatus 100 further includes a control system 150 that controls the activation of the data acquisition and processing systems 105 and 107. The control system 150 determines the number of measurements that should be made in order to generate a spectrum having desired noise characteristics, as described below.

[0023] The data acquisition system 105, which acquires the NMR response signals, includes components well known in the art. For example, the data acquisition system may include a measurement subsystem for measuring NMR response signals, and a signal averaging subsystem for averaging the measured signals over many measurements to lower the noise content in the signals. In signal averaging, the signal grows relative to noise by a factor $\sqrt{N_{tr}}$, where N_{tr} represents the number of measured transients. The measurement subsystem typically includes an NMR transmitter for generating RF excitation pulses and delivering the pulses onto an NMR sample, and an NMR receiver for detecting the response signals emitted by the sample in response to such an excitation. NMR transmitters and receivers are well known in the art and commercially available. The signal averaging subsystem is also a standard component in NMR signal processing, and includes processing subsystems for receiving and storing an acquired transient after each measurement, and for averaging over all of the acquired and stored transients.

[0024] The signal averaging subsystem averages the corresponding sample points over all the transients. In this way, an averaged signal (sometimes called "ensemble averaged signal" in the art) is generated in which signal-to-noise correlations are very small, and which have a lower noise content than any single signal measurement or transient. The averaged signal may be represented as a discretized set of N sampled data points c_n (n = 0, . . . , N-1).

[0025] In one embodiment, the data processing system 107 implements a signal processing scheme which is based on harmonic inversion, and which allows for spectra of satisfactory quality to be obtained while averaging over a greatly reduced number of transients. By "satisfactory" quality, it is meant that the error margin is within the standards accepted in the industry, and that there are no false or missing spectral lines. In overview, the data processing system 107 includes a noise reduction preprocessor 130 for transforming the averaged signal into a noise-reduced signal, and a spectral estimator 140 for converting the noise-reduced signal into a frequency domain to generate the desired spectrum. Preferably, the data processing system 107 also includes a windowing capability which breaks the Fourier transformed signal into "windows," i.e. into regions of smaller bandwidth.

[0026] A windowing program in the data processing system 107 applies a windowing filter to the averaged signal that is outputted by the data acquisition system 105. In one embodiment, the averaged signal is fast Fourier transformed, and the fast Fourier transformed frequency domain signal is broken into windows of 200 to 500 Fourier grid points. The window size that is most commonly used is about 300 Fourier grid points. While the method and system of the present invention can be implemented without the windowing step, windowing provides many advantages for the noise reduction portion of the signal processing described in this section. Without windowing, the singular value graphs (discussed below) become too cluttered with signal and noise singular value points to be easily analyzed. Also, because certain windows are much simpler to process than others, if the windowing step is omitted all features become unnecessarily tied to the features most affected by noise. Finally, without windowing the dimensions of a matrix that must be generated and diagonalized in order to solve the harmonic

inversion equations may become too large, and as a consequence the needed diagonalization routine may become too time consuming.

[0027] When harmonic inversion is used, windowing creates a smaller signal of length N_d which is much smaller than N, and which is valid only within the window. Resolution is not affected by this signal length reduction. The length N_d of the smaller signal determines, in turn, the dimensions of the systems of equations to be solved in harmonic inversion, the dimensions being given by $N_d/2$. Since these equations have a rank less than their dimension $N_d/2$, they are ill-conditioned and unstable, and the results are very sensitive to small perturbations.

[0028] The edges of the windows are at the Fourier grid points. Ideally, their placement would surround the regions of the signal, and begin and end in regions of pure noise. In less than ideal situations a systematic windowing of the spectrum can be designed for all regions. If, because of spectral density reasons, peaks unavoidably appear at window edges where window induced distortions will occur, an additional window should be chosen so that the edge of the prior window falls interior to the new window.

[0029] The windowing filter is a "decimation" window, which when applied to the averaged signal c_n (n = 0, . . . , N-1) produces a decimated, band-limited signal of length N_d from the measured averaged signal c_n of length N. The decimated signal will be referred to in this section as c_n^d (n = 0, . . . , N_d-1). The signal length N_d of the decimated signal is substantially less than the signal length N of the measured averaged signal. The decimated signal c_n^d is inputted into the noise reduction preprocessor described below. In a typical Fourier spectrum of a signal made of a given number of transients, all intensities outside the window of N_d Fourier grid points are set to zero. The window spectrum is then shifted symmetrically about zero frequency and inverse Fourier transformed, to produce a decimated time signal. The original bandwidth, given by $2\pi/\tau$ where τ is the sampling period, is now reduced by a factor of N_d/N. The effective sampling period of the decimated signal is given by $N_\tau / N_d \equiv \tau_d$, which is substantially greater than the original sampling period τ.

[0030] The noise reduction pre-processor 130 takes the decimated signal and creates a low noise signal therefrom. In one embodiment, the noise reduction pre-processor 130 includes: 1) a matrix generator that constructs a correlation matrix from the decimated signal, 2) a matrix diagonalizer that diagonalizes the correlation matrix to extract the singular values (i.e. the real, non-negative eigenvalues) and the corresponding eigenvectors, and 3) a signal projector that projects the decimated signal onto the noisefree subspace to generate noise-reduced signals.

[0031] In one embodiment, the matrix generator generates the correlation matrix within an M-dimensional vector space defined by the decimated signals c_n^d (n = 0, . . . , N_d-1). Specifically, from the N_d decimated time signal samples c_n^d, a number $N_d - M + 1$ of linearly independent, M-dimensional measured signal vectors $\vec{c} = (c_n, c_{n+1}, \cdots, c_{n+M-1})$ are created, to define an *M*-dimensional vector space. The measured signal vectors are then written as a sum of a noiseless signal vector $\vec{x}_n$ and a random noise vector $\vec{\varepsilon}_n$. In this way, the vector space defined by these M-dimensional measured signal vectors includes a noisefree signal subspace, and a random noise subspace.

[0032] It is known that the noisefree NMR, EPR etc. FID signal of chemical samples are made of K complex harmonics. A basic assumption of the harmonic inversion method is that the noiseless signal elements x_n are created from a sum of *K* damped harmonics, i.e. that the spectrum is the sum of *K* complex Lorentzians. *K* is the rank of the observed spectral peaks. In harmonic inversion, the noisefree signal vectors are written as a finite sum of damped harmonics. The noise vectors cannot be similarly fitted.

[0033] Specifically, the noiseless signal vectors are written vectorially, and sample by sample, as:

$$\vec{x}_n = \sum_{k=1}^{K} d_k z_k^n \vec{s}_k \; and \; x_n = \sum_{k=1}^{K} d_k z_k^n \qquad (2)$$

[0034] where $(\vec{s}_k)^T = \left(1, z_k, \cdots, z_k^{M-1}\right), z = \exp(-i\omega_k \tau_d)$.

[0035] In equation (2) above, d_k represents the weight of the K-th harmonic, and ω_κ represents the complex frequency of the k-th harmonic.

[0036] In equation (2), z_k is a damped exponential in the time domain. The real part of ω_k is the frequency and the modulus of the imaginary part $|Im(\omega_k)|$ is twice the width of the Lorentzian of height $d_k / |Im(\omega_k)|$. The rank or dimension of the signal space *K* is not an input, and is determined by the processing. Since the vectors $\vec{s}_k$ are linearly independent, they form a basis set for a signal space in which the signal vectors $\vec{x}_n$ must lie.

[0037] From the decimated signal c_n^d, the matrix generator constructs a *M*-by-*M* Hermitian covariant correlation matrix R_{ij} (i = 1, . . . , M; j = 1, . . . M) in accordance with the following formula:

[0038] $$R_{ij} = \frac{1}{N_d - M + 1} \sum_{n=0}^{N_d - M} c_{n+i-1} c^*_{n+j-1} \quad (3)$$

[0039] Using a standard diagonalization routine, the matrix diagonalizer diagonalizes the correlation matrix *R*, thereby obtaining the singular values u_i and their corresponding eigenvectors $\vec{u}_i, i = 1, \cdots, M$. The singular values are the real, non-negative eigenvalues of the correlation matrix. The singular values are indexed so that $u_i > u_{i+1}$. After a sufficient number of transients, the signal projector projects the measured vectors onto the noisefree signal subspace, the projections representing the noise-reduced signal vectors.

[0040] The singular values can be divided between noisefree singular values, associated with the noisefree signal subspace, and the noise singular values associated with the noise signal subspace. In order to determine whether a sufficient number of transient acquisitions have been made, for purposes of obtaining a noise-reduced spectrum, a graph of ln (u_i) against the index *i* is produced.

[0041] The user or operator of the apparatus 100 determines whether a separation or a "gap" between the first noise point (i.e. noise singular value) in the plot, and the smallest signal point (i.e. noisefree singular value) in the plot, can be identified. This provides a first criterion for recognizing that the iterations performed so far may be close

to being sufficient for purposes of producing an acceptable spectrum. The user or operator then determines whether the gap stabilizes over a number of additional measurements, signal-averaging, and singular value generation, described above. This provides a second criterion for recognizing that a sufficient number of transients has been acquired. As a supplemental criterion, the operator may also determine whether the spectrum also stabilizes over a number of additional measurements.

[0042] In the method and system described in this section, the interactivity is with the singular value graph, not with the signal-to-ratio ratio that is monitored as the transients are being acquired, in contrast to known methods, such as the FFT (fast Fourier transform) method. When the FFT method is used, transients are taken and signal averaging is performed, until the desired signal-to-noise ratio is achieved. In practice, the operator watches the noise decrease, and watches the signal "rise out" of the background. This is not done here. Instead, the criterion for stopping the acquisition of transients is the appearance of a stable gap in the singular value graph, and, supplementally, the appearance of a stable spectrum.

[0043] As an alternative to user interaction with the singular value graph, the control system 150 can be configured to determine whether the criteria described in paragraph 35 have been satisfied. For specific types of spectroscopy, spectrometers, active nuclei concentration, and physical parameters, calibrations can be made as to when the gap will appear. These calibrations do away with the need for user interactivity, in which case the control system 150 can be configured to determine: 1) whether a clearly discernable gap has appeared between the smallest signal point and the first noise point in the plot of singular values; and 2) whether the gap has stabilized with respect to further acquisition of transients by the data acquisition system 105. In this embodiment, once the control system 150 determines that such a gap has appeared and stabilized, the control system 150 sends command signals to stop the data acquisition system 105 from making further measurements.

[0044] The appearance of the gap and the stabilization of the gap establish that a sufficient number of transients have been performed for noise reduction to be implemented, for K to be estimated, for a local signal-to-noise ratio to be 1, and for

transient collection to stop after roughly another 5% to 10% of the already collected transients have been obtained. The extra number of transients is needed to test the convergences, i.e. to check that the gap has stabilized and remains stable, and that the spectrum has also stabilized.

[0045] In one embodiment, the control system 150 may include a graphics system 151 that receives as input the singular values obtained by the noise reduction preprocessor 130, and generates a plot of the singular values as a function of their indices. While a logarithmic plot is described and discussed in this section, non-logarithmic plots can also be used. The control system 150 further includes a pattern recognition system 152, which is configured to identify, from the singular value plot generated by the graphics system 151, a gap between the smallest noisefree singular value and the first noise singular value. The control system 150 further includes a command signal generator 153 which is responsive to the pattern recognition system 152. The command signal generator 153 is configured to generate an output signal that requests the data acquisition system 105 to make more transient acquisitions (i.e., a "not OK" signal as illustrated in Fig. 1), if the pattern recognition system 152 fails to identify such a gap, or if the gap identified by the pattern recognition system 152 fails to converge. The command signal generator 153 is configured to generate an output signal that requests the data acquisition system 105 to stop making any further measurements (i.e., an "OK" signal as illustrated in Fig. 1), if the pattern recognition system 152 establishes the appearance and stabilization of such a gap.

[0046] The control system 150 may include a computer-readable medium that has stored therein computer-readable instructions for a processor. These instructions, when read and implemented by the processor, cause the processor to perform the steps described in paragraph 37 above, namely: 1) identify a gap between a noisefree singular value (associated with the noisefree signal subspace) and an adjacent noise singular value (associated with the noise subspace);
2) request further measurements by the data acquisition system 105 if the gap cannot be identified; 3) if the gap can be identified, determine the stability of the gap; 4) request further measurements by the data acquisition system 105, if the gap does not stabilize; and 5) request that no further measurements be made by the data acquisition system

105, if the gap has stabilized. The computer-readable medium may be any medium known in the art, including but not limited to hard disks, floppy diskettes, CD-ROMs, flash memory, and optical storage devices. The computer readable instructions discussed above may be provided through software that is distributed through the Internet.

[0047] The gap represents the numerical separation between the eigenvalues associated with the noisefree signal subspace and the eigenvalues associated with the noise subspace. Perturbation theory indicates that groups of eigenvalues that are well spaced are much less sensitive to perturbations that eigenvalues that are close together. Therefore, the well-spaced eigenvalues can be identified with the noisefree signal, and the regions of high density eigenvalues can be identified with noise. Perturbation theory also indicates that the noise subspace has less influence on the noisefree signal subspace as the gap increases in size. When changes occur or when no "gap" can be clearly estimated, then the number of transients used needs to be increased and the whole process must start again.

[0048] When it is established by the user or by the control system 150 that a clear gap has appeared and stabilized, the signal projector in the noise reduction pre-processor 130 generates a noise-reduced signal, so that a spectrum can be formed by frequency inversion. The signal projector projects the decimated measured vectors onto the noisefree signal subspace, using the following projection formula:

$$\vec{c}_n^{\,or} = \sum_{k=1}^{K} (\vec{u}_k^{\,*}, \vec{c}_n)\vec{u}_k \qquad (4)$$

where $(,)$ denotes the scalar, inner product of two vectors, the asterisk denotes a complex conjugate, and u_k represent the eigenvectors corresponding to the singular values.

[0049] Given the decimated signal vectors $\vec{c}_n$ an estimate of the $N_d - M + 1$ projected signal vectors can be made, as $\vec{\chi}_n \cong \vec{c}_n^{\,nr}$. Since a particular $\chi_n \cong c_n^{nr} = c_n^{NR}$ element appears in multiple vectors, an arithmetic average is taken, the result of which restores the Hankel structure of the signal matrix as defined by $\chi_{nm} = \chi_{n+m}$. As this averaging

tends to cancel some of the corrections made in the projection, starting with the new signal the whole procedure is iterated to convergence several times, to give the final noise-reduced or "cleaned" signal.

[0050] The noise-reduced signal, consisting of discretized sampled points c_n^{NR}, is input into the spectral estimator 140, which converts the signal into frequency space by using known conversion methods such as harmonic inversion or Fourier transform, to derive a noise-reduced spectrum. Among the known methods, using harmonic inversion for the frequency conversion step gives the best results, while using the Fourier transform methods for the frequency conversion step provides improved results.

[0051] Fig. 2 illustrates a 1D 13C NMR absorption spectrum of a 15 mM solution of strychnine in $CDC1_3$ for a carbonyl spectral region. The spectrum in Fig. 2 shows the chemically shifted singlet lines in a window. The spectral parameters were obtained with an acceptable level of accuracy on a twenty year old AM-360 MHz machine with a 5 mm diameter tube. The left column in Fig. 2 shows the results after 128 transients, with N = 16384 samples, were measured and averaged. The right column shows the result after 256 transients were measured and averaged. The total acquisition time was 8 min. 15 sec., and 16 min. 30 sec., respectively. While times vary among different machines, tube size and concentration, the comparisons were made between the same machines, tubes and concentrations.

[0052] The experiment was performed with the knowledge that carbonyl was in the molecule, and that it was expected to give the lowest amplitude signal of all the carbons. The signal was expected to be in the 161 to 175 ppm region, so two windows were placed in each of 512 Fourier grid points. At 256 transients (N_{tr} = 256) a converged result was obtained, so that any further acquisition of transients was discontinued. The second column in the figure is shown to demonstrate convergence of the processing. The legend "CS" in the figure denotes "cleaned signal," while "NS" denotes the original noisy signal. "MF" denotes the "matched filter" variant of Fourier noise reduction processing. "HI" indicates that the harmonic inversion spectral estimator was used, while "FFT" indicates that the Fast Fourier Transform spectral

estimator was used. The harmonic inversion spectrum, not being on a Fourier grid, was drawn on a thousand points grid in the window of the spectrum in the figures.

[0053] Figure 3 illustrates the singular value analysis for the spectrum shown in Figure 2. The plot in Fig. 3 was generated for a noisy signal after 128 (first column) and 256 (second column) transients, respectively. The singular values are not shown for M > 30. Starting with an N = 16384 signal, 256 transients were needed before the singular value plot, which previously showed no gap for 128 and 192 transients, converted to a plot with a clear gap with K = 1. At this point the signal-to-noise ratio was 1. A K = 1 gap showed up as these signals had less noise. Figure 3 shows that an excellent spectrum results when the full length signal for 128 and 192 transients was assumed to have K = 1, and projection was done on the first eigenvector. To test the 256 transient result, which was accepted as a convergence, an experiment with 2560 transients was also done. The 2560 transient experiment, by signal averaging, has a signal-to-noise ratio that is higher by a factor of about 3. Figure 3 shows it gave the same K = 1 result and the spectrum (not shown) was the same as the N_{tr} = 256 spectrum, except for a small line narrowing. Linewidths are always instrumental.

[0054] As seen from the Fig. 3, and most clearly from the 2560 transients experiment, the noise singular values form a quasi-horizontal string, resembling a string of pearls, to the lower right of the smallest signal point, i.e. the smallest noisefree singular value. Windowing bends the true horizontal line without prejudicing the gap. The distance from the first noise point to the smallest signal point is the gap that is being identified. The gap between the noise singular values and the noisefree singular values is clearly seen in the 256 transient and the 2560 transient results in Figure 3. The gap appears even if the noise eigenvalues are not constant. In most case, the gap can be begun to be estimated by recognizing that it always appear at the elbow of curves, as seen from Figure 3. The qualitative change in the eigenvalue density and spacing (low on the left and high on the right) is an indicator of a gap.

[0055] Fig. 4 illustrate the 1D INADEQUATE, spin-spin interaction ^{13}C-^{13}C spectrum of a 5% solution of dicyclopentadiene in $CDC1_3$ for the 4th carbon spectral region, for a noisy signal after 2432 and 2560 scans of length $N = 32K$. Pure signal averaging is

estimated to use 2 weeks of scanning for similar results. The arrangement of plots in rows is similar to that in Figure 2. The FID signal from the 1D INADEQUATE experiment was studied, in order to further demonstrate the ability to save transients, using the method and system described above. Windows surrounding the 4th carbon at 54.75 ppm, in a number scheme that increases with decreasing ppm, were used as an example of a typical case. The foreknowledge was the position of the singlets, and the order of magnitude of the splitting, which made the choice of windows easy. It was noted that K could be slightly more than twice the number of splittings, due to the fact that the singlet central line was not totally wiped out and in fact could appear as several lines.

[0056] To start, 2176 scans (not shown) were tried first, with and both N = 16384 and 32768 for the fourth carbon. The former gave K = 7, the latter K = 6. For the purposes of estimating K , it was surmised that the less noisy K = 7 was correct. To be certain, the number of transients N_{tr} was raised to 2432 and 2560. Both cases gave a clear K = 7 at both half and full lengths and a converged spectrum, as seen in Figure 4.

[0057] Figure 5 shows the corresponding SVD curves, for signal lengths of N = 16384 and 32768, and transient numbers of 2432 and 2560, respectively. A clear gap, which is stable with respect to the increase in transients (from 2432 to 2560), can be readily discerned between the last one of the relatively well-spaced, noisefree singular values, and the first one of the closely spaced, noise singular values. The data acquisition time used was twelve hours as opposed two weeks. The data acquisition time, or machine run time, was saved by a factor of at least about 10, and up to about 100.

[0058] In sum, the technique of the present invention allows for satisfactory spectra to be generated while using substantially fewer transients than are typically acquired for NMR spectral studies, by supplying the criteria for recognizing when transient acquisitions may stop while still deriving a satisfactory spectrum from already acquired transients. The method and system of the present invention permits a spectrum (having acceptably low noise characteristics) to be generated after performing measurements that are fewer by a factor of at least about 10 and up to about 100, compared to the number of measurements required in order to generate a spectrum having a

comparable signal-to-noise ratio, using signal averaging followed by fast Fourier processing. In other words, a great deal of measurement time is saved. Because machine time is generally very expensive in spectroscopic techniques such as NMR, the saving in measurement time translates into substantial cost savings.

[0059] While the invention has been particularly shown and described with reference to specific preferred embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.